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ROLE OF ICE PROPERTIES IN WAVE-ICE INTERACTION DURING LIMEX '1987

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ABSTRACT

The Labrador Ice Margin Experiment (LIMEX) was initiated as a pilot program in March, 1987. An interdisciplinary group of different research organizations gathered data from the Marginal Ice Zone (MIZ) and in the open waters adjacent to the ice edge. This paper presents results of the 1987 pilot program.

The Ocean Data Gathering Program (ODGP) spectral ocean wave model was used to hindcast wind and wave fields for the duration of the experiment. In addition, the C-CORE/MUN ice motion package (6 degrees of freedom) was placed on several ice floes to measure the wave induced ice motion at different locations along the MIZ. Analysis of the motion package records furnished time series plots of wave parameters as well as wave spectra within the ice cover. Interpretation of the aerial photographs provided measurements for floe size distribution, floe density and ice concentration.

Keywords: wave ice interaction, sea ice cover, wave attenuation, wave patterns in SAR imagery.

INTRODUCTION

The Labrador Ice Margin EXperiment (LIMEX) is directed to advance the knowledge of the natural processes operating during the formation, existence and decay of the sea ice cover off the east coast Canada. The first field program for LIMEX was carried out in March 1987. It was conducted as a pilot project to gather field observations and field experience of the sea ice cover at the ice transition to ocean, "the marginal ice zone", of the northwest Atlantic. This is a complex and dynamic zone is one of considerable economic importance for renewable and non-renewable resources in Canada.

The LIMEX '87 pilot project was encompasses careful documentation of observations, evaluation of measurement techniques and the formulation of hypotheses. The chief interest of the authors was to observe and quantify wave ice interaction. It is postulated that the ocean waves incident at the ice edge are crucial in the genesis of the ice conditions encountered at the ice margin. On the other hand, the ice cover plays an important role in determining the nature of the ocean waves generated at the ice edge and the character of waves propagated within the ice cover.

The winter ice cover at lower latitudes in the northwest Atlantic is an extremely variable phenomenon. This was illustrated dramatically through the LIMEX '87 project time period. The ice cover which initially stretched 400 km east from the Newfoundland coast. During the 9 days from March 9 to 23, however, this ice cover was compressed by persistent easterly winds into a narrow strip adjacent to the coastline through due to (McNutt *et al.*, 1988). This stable weather condition provided a rare opportunity to observe the effects of wave action on an ice cover with a well defined edge.

The marginal ice zone is a difficult place to conduct oceanographic and ice cover measurements. Wave buoy moorings cannot be set because of the high risk of having equipment swept away by the moving ice. Often the ice is too thin and motions too severe to set and recover instrumentation from the ice floes.

The ice motion instrumentation employed during LIMEX '87 was designed to measure the wave induced motions of bergy bits and growlers. The equipment was not ideally suited to collect the extended time series desired for wave investigation.

The LIMEX program included a major remote sensing component. This focussed on the evaluation of a prototype synthetic aperture radar (SAR), the sensor unit which is being developed for the RADARSAT platform. The wide coverage of the SAR imagery provides a exceptional opportunity for fitting local observations into a regional picture.

MATERIAL PROPERTIES OF FLOE ICE COVER

The incident ocean waves furnish the driving force while the ice cover offers resistance to the transfer of this wave energy through the ice cover. When a radiating wave field encounters a material boundary, a fraction of the wave energy passes (is transmitted) into the ice cover and a fraction is reflected. The ratio of energy transmitted and reflected depends on the equivalent of the index of refraction (optics) of wave propagation in an ice cover. There is little known about the physical properties which dictate wave propagation and wave reflection in discrete floe ice cover.

Wadhams *et al.* (1986) suggest floe size distribution to be an important property controlling wave attenuation in ice cover. Their study was conducted in a pack ice regime composed of large floes (~100 m). The LIMEX'87 work was conducted in ice cover consisting of much smaller mean floe size, (~5 m). Here other ice cover features appeared to have an important effect on the wave ice interaction. LIMEX '87 observations of wave ice interaction suggest that collisions at floe boundaries and within the ice debris filling the interstitial area between discrete floes have an important influence on the ice cover's resistance to wave propagation.

Lateral movement of the ice floes during convergence produces in two significant changes in the nature of the ice cover. (1) Any pulverized ice is squeezed and forced down to underlie the discrete floes and (2) the floes are rotated and jostled so that the interstitial area between the floes is minimized. Hence the floes interlock and offer increasing resistance to further lateral movement and to bending motion from wave action. The compaction of the pack is a time varying property and depends on prior mechanical activity, i.e. the mechanical history for the ice cover. The increase of ice cover strength (resistance) caused by convergence is commonly know as "ice pressure". It offers considerable resistance to vessel movement and can even beset capable ice breaking vessels. The "pressure" condition will persist as a feature of the pack ice condition after the lateral load which created it has passed. Further exposure to wind and current loads, new wave action or a combination of both will act to disperse the ice and relieve the ice pressure.

During LIMEX '87 the available measurement techniques were not specifically designed to quantify the material properties which could resist or enhance wave propagation of the ice cover. More basic research needs to be done to yield fundamental results for wave action in sea ice cover. The LIMEX '89 field program will spend additional time on this topic. Any advances in the identification of "pressured ice" especially remote sensing identification by the ice reconnaissance services will produce significant economic benefits to companies routing vessel traffic through ice covered waters.

FIELD OBSERVATIONS

Ice Motion Measurement

Ice floe motion measurement was accomplished with the C-CORE/MUN six-degree of freedom ice motion package (Lever *et al.*, 1986). This unit was originally designed to measure wave induced iceberg and growler motions and was employed without modification. The sensor cluster uses three orthogonally mounted accelerometers to detect displacement. The two instruments used in 1987 had different methods of measuring pitch and roll; package B used a gyro and package C had a set of tiltmeters. The angular measurements are required to transform the local instrument axis to a fixed reference frame. There is still some question about the validity of tiltmeter measured rotations when these sensors are faced with a combination of rotation and acceleration.

An investigation of the directional wave spectra and a more complete comparison of ice motion with the incident ocean wave regime is given a fuller treatment to a separate paper by Eid *et al.* (1989).

Incident Wave Field

Wave measurement at the ice edge was carried out with a Delft disposable wave buoy, on March 22 and 23, 1987 (Thomas, 1988). The wave field was hindcast using the meteorological data and the Ocean Data Gathering Program (ODGP) model for all the observation periods.

Remote Sensing

The C Band SAR imagery collected by the Canadian Centre for Remote Sensing's Convair 580 aircraft provided extensive coverage of the marginal ice zone through LIMEX '87. Coverage on March 23 and 26, 1987 was of particular interest to the wave ice interaction program. The SAR imagery covered from 3 to 3.5 degrees of latitude and full coverage from the Newfoundland coast to the ice edge to the east. The SAR imagery provided a unique opportunity to view the wave ice interaction process on a regional scale.

Floesize Distribution

Aerial photographs were taken from a helicopter at 600 m to access the granular nature of the ice. A 70 mm Hasselblad camera with a 80 mm focal length lens was used with Kodak Aerographic Plus-X black and white film. Ice coverage photography consisted of a series of 60 to 100 square frames of 400 m on the side except for one day when the ceiling was restricted to 300 m and the photograph frames were 200 m on the side.

Floe sizes were taken from 73 frames for March 23, 25 and 26, 1987. Each photograph was sampled by measuring floe diameters for every floe occurring on a set of lines that was superimposed on the photograph. The floe dimensions were obtained using a vector digitizing table. This sampling technique yields a floe size distribution that is normalized by floe area. Figure 1. illustrates a typical floe size distribution. Table I. summarizes the results for some locations of interest to the wave ice interaction investigation.

Case I - Dispersed Ice Floes

The first deployment of the ice motion package took place on March 22, 1987. The instrument was placed on a small floe, (~5 m), in a strip of loosely packed floes, < 10 m. All the floes were surrounded by water; adjacent floes were not colliding. Figure 2. shows the non-directional wave field estimated from the ice motion data collected. Simultaneous measurements by the John Hopkins University waverider in adjacent open water (Thomas, 1988) gives the wave height entering the pack at 2.3 m and a dominant period of 9 seconds. The "CSS Baffin" was operating in limited visibility when the measurements were conducted. There was no collaborative helicopter photography of SAR imagery on March 22, 1987.

Case II - Definite Transition

March 23, 1987 proved to be a significant observation period for wave ice interaction. It was unfortunate that the ice motion package failed to record data during that deployment. The ancillary observations are valuable for the study and are reported.

The swell in the ice cover was evident visually and has been reported by McNutt *et al.* (1988). The

SAR imagery of the ice cover of the "CSS Baffin's" operations area showed a marked transition about 4 km into the ice cover. The transition was from a homogeneous, wave patterned texture seaward, to a floe patterned texture for the ice cover landward to the coast. The decreasing wave pattern observed in the ice cover with homogeneous radar return suggested the wave propagation into the ice cover was significantly attenuated by the time the waves had travelled to the transition zone. The floe size distributions for the transect across the ice belt showed a marked reduction of floe size immediately adjacent to the ice edge. Waverider measurements on March 23, 1987 showed the incident wave field having a 2.5 m significant wave height.

Case III - Wave Attenuation

A seven hour period was dedicated to the ice motion measurement on March 25, 1987. Sensor package C was placed on a small ice floe, (~3 m), adjacent to the ice edge. Its motion was recorded for 5.5 hours. Package B was deployed three time at three different locations, nominally at 1, 2, and 4 km into the ice pack. Figures 3. (a), (b), and (c) give the non-directional spectral densities for each deployment. For comparison Figure 4., shows the waves attenuating and the shorter period waves disappearing with distance away from the ice edge. The energy attenuation is summarized as: -3.9 dB with dominant period of 8.7 seconds at 1 km, -8.3 dB and period 9.5 seconds at 2 km and -11.4 dB and period 18.1 seconds at 4 km.

The helicopter aerial photography showed the floe size distribution to be relatively uniform over the ice cover attenuating the wave field, (see Table I). The floes were relatively closely packed. The marked attenuation of the waves over a relatively short distances indicated the ice cover energy absorption mechanisms were effective through the observation period.

Case IV - Wave Penetration

Ice motion measurements, helicopter aerial photography and SAR coverage were obtained for March 26, 1987. The motions measured at the two stations, one is given in Figure 5. The non-directional spectra showed a long period swell, 15 seconds, propagating in the ice cover with little attenuation, -1.7 dB, between the stations. This observation was collaborated by visual observation of the swell running in the ice cover and the SAR imagery collected for the same time period. The SAR imagery showed a uniform wave pattern for the whole ice cover along the east coast of the Avalon. The apparent wavelength for the swell was estimated at 300 m.

The more complete penetration by the ocean waves through the ice cover during this period of observation might be attributed to two factors. (1) The longer period wave incident at the ice edge, 15 seconds as compared to 8 to 9 seconds on March 25. (2) The ice cover appeared to have more separation between the floes then the ice cover sampled on March 25. Techniques need to be developed further to characterize the granular nature of pack ice cover.

DISCUSSION

The observations of the LIMEX '87 project showed that the wave ice interaction is a complex phenomenon and the marginal ice zone cover is a complicated material. The discrete floe composition of sea ice cover is analogous to a granular material (Erlingsson, 1988). It seems to behave like a two dimensional granular material with particle sizes large compared to thickness. The third dimension is the ice thickness which is also an important factor in assessing ice cover strength. The average strength of the particular ice cover dictates how the incident wave field crosses the ice edge and propagates within the ice cover.

Wind and current act on the air/ice and ice/water boundaries causing the floes to converge (compact) and disperse; this depends on the direction of the applied loads and boundary restraints on the ice cover. Ice convergence strengthens the ice cover and increases its resistance to the radiation of the wave action. The SAR imagery of March 23, 1987 showed an ice field with considerable lateral strength. The major portion of the wave energy appeared to be attenuated in a narrow band of ice adjacent to the ice margin.

Subsequent motion measurements and SAR imagery, on March 26, 1987, showed the wave field propagating further into the ice cover. Results indicated that the ice cover strength changed with time. The associated surface measurements suggested the decrease in strength was caused by a combination of reduced wind stress and the gradual wave action on the floes. The accumulating volume of crushed ice between the floes suggested the relative movement between floes caused continual failure at the floe perimeter. Jordaan and Timco (1988) have investigated the role of crushed ice during the ice-crushing process and have shown that this viscous ice material consumes the largest part of the failure energy involved.

The crushed ice appears to perform a somewhat different function in wave ice interaction. The crushed ice flows into the interstitial area between the floes lowering the flexural strength of the granular ice cover. The weakened cover permits the wave field to radiate deeper into the ice cover where the process continues. While wave energy attenuation can be approximated by linear potential theory (Wadhams *et al.*, 1986, 1988), the attenuation coefficient is dependent on wavelength of the incident wave field (Eid *et al.*, 1989) and on the material properties of the ice cover involved. Therefore the attenuation coefficient can be expected to vary rapidly as the ice cover converges and disperses, and as the ice crushed and ground by wave bending and floe to floe collisions. Although thermodynamic effect of re-freezing was not encountered through the LIMEX '87 period it must be assumed to have a significant effect on the behaviour of the winter marginal ice zone.

SUMMARY

The results collected during the field experiment do not conclusively confirm the relative importance of floe size distribution in the attenuation of ocean waves in the marginal ice zone. The authors speculate that the wave penetration is a major factor in dictating the floe size distribution. Further work is planned on the mechanical behaviour of ice floes in a wave environment. It is clear that the ice cover is effective in filtering the wind waves. The spectra of the ice motion time series indicates the ice cover encountered during LIMEX '87 behaved like a low-pass filter with a roll off at about 0.2 Hz.

Other features like floe to floe separation (compactness), frequency of floe collisions, floe to

floe interlock and fraction of ground ice appear to have a more direct effect on wave ice interaction. The interactions are a function of the spatial distribution of the ice cover. It is not yet clear how to assign quantities that will be effectively correlated with the mechanical relationship (model) for wave ice interaction. The helicopter aerial photographs and the SAR imagery are two data sets that might be applied to extract this sort of information. Both techniques offer limited temporal coverage. It is planned to investigate these concepts with image capture and analysis techniques to explore ways to quantify the granular nature of sea ice cover.

Much more complete data collection will be required before it will be possible to apply these results to help estimate of risk of ice loads at offshore structures. Future results may prove that offshore platform may not need to be designed to the break continuous ice cover. The combination of wave and ice loads may represent a lower environmental load than either wave or ice loads acting independently. The objective of LIMEX '89 is to collect a more extensive data set under a different set of conditions, add to the data base of ice conditions and aid the engineering of safe and economic systems to recover both renewable and non-renewable resources from Canada's ice covered oceans.

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TABLE I

SUMMARY - FLOE SIZE DISTRIBUTIONS

location	mean floe size (m)	std. dev. (m)
March 23, 1987		
ice edge	4.3	2.1
mid-point	4.8	3.2
near coast	9.9	7.3
March 25, 1987		
ice edge	9.8	6.7
2km from edge	7.3	5.3
4km form edge	10.9	7.3
March 26, 1987		
across the pack		
ice edge	5.4	3.4
mid-point	7.7	4.7
at coast	18.0	11.1
along coast		
north end	6.7	3.6
at ship	7.0	3.7
south end	7.1	3.7

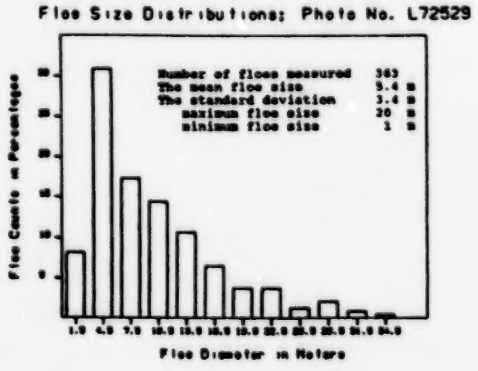
Floe Size Distributions: Photo No. L72529
Number of floes measured 363
The mean floe size 5.4 m
The standard deviation 3.4 m
maximum floe size 20 m
minimum floe size 1 m
Floe Count in Percentages
Floe Diameter in Meters

Figure 1. A typical floe size distribution for the ice cover encountered in LIMEX '87.

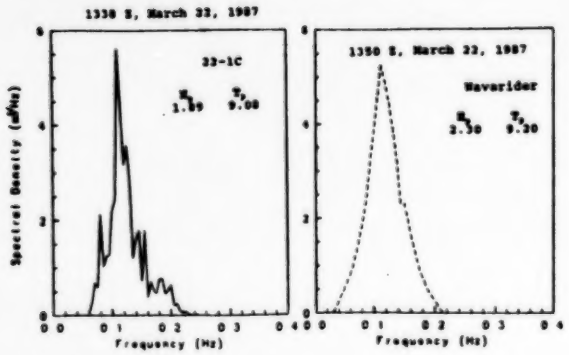

Figure 2. The non-directional spectra density for ice floe motion and waverider on March 22.

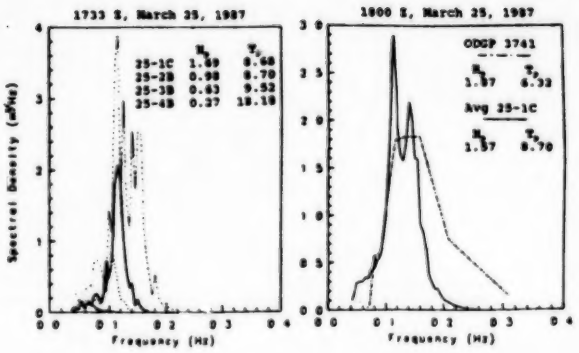

Figure 4. Comparing the spectra of Figure 3 with the ice motion at the ice edge and concurrent ODGP wave hindcast.

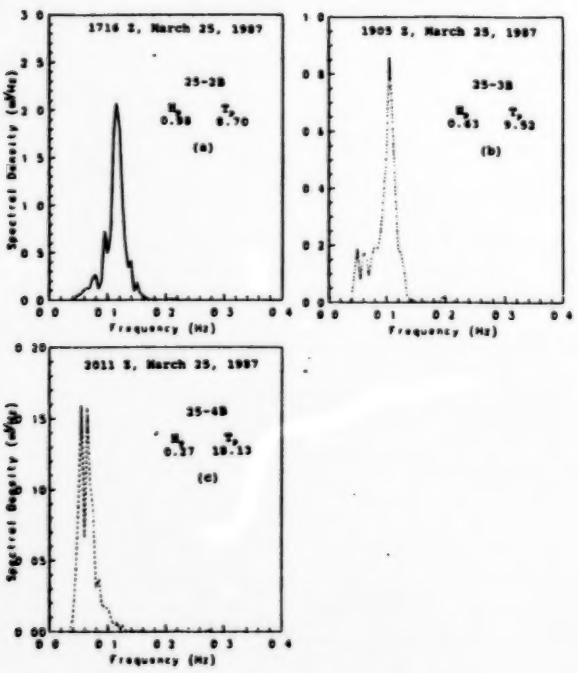

Figure 3. The wave spectra densities showing attenuation with distance, (a) 1 km, (b) 2 km, and (c) 4 km.

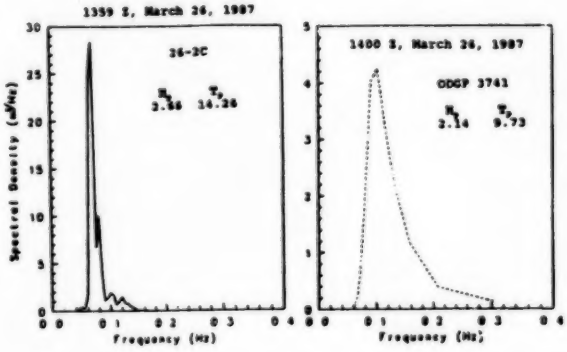

Figure 5. The ice motion and wave hindcast on March 26 with the long period swell in the ice cover.